A collisional model of the "pristine zone" of the Main Asteroid Belt and the dynamics of LHB families located there

Miroslav Brož, Helena Cibulková, Matyáš Řehák - Charles University in Prague, V Holešovičkách 2, 18000 Prague, Czech Republic, email: mira@irrastro.mff.cuni.cz

Abstract: Modifying the Boulder code (Morbidelli et al. 2009), we construct a new collisional model of the Main Asteroid Belt, which is divided to six parts (inner, middle, outer, pristine zone, Cybele region and high-inclination region) in order to study relations between them and check the number of observed families. We extend our collisional models and include the effects of the Late Heavy Bombardment too. In the framework of the Nice model, the flux of comets during the LHB is mostly controlled by the original size-frequency distribution of the cometary disk beyond Neptune and the rate at which comets disrupt when they approach the Sun. To this point we provide a related discussion of various cometary disruption laws.

1. Observational data:
- AoD/DR (2008), AoD/YS (Knežević & Milani 2010) and WISE (Masiero et al. 2011) catalogs
- five parts separated by mean-motion resonances with Jupiter, the small-mass formed by asteroids with high proper inclinations (Figure 1)
- their size-frequency distributions (Figure 2) are calculated from asteroids available from WISE
- the individual SFDs differ significantly in terms slopes and total numbers of asteroids.
- the up-to-date list of observed families is taken from Brož et al. (2012)

2. Initial conditions and parameters of collisional simulations
- mutual collision probabilities and impact velocities were calculated between each pair of populations
- to define the shape of initial SFDs (i.e. slopes in 3 size ranges and normalization) we fit currently observed SFDs scaling laws parameters: Benz & Asphaug (1999) for boulders and 100 km asteroid collisional reorientations (Brož et al. 2012), the Boulder collisional code operates with a random seed - for more reliable results we thus run 100 simulations
- the final SFDs after 4 Gyr are shown in Figure 4, good fits for D > 10 km, but below D < 5 km are final SFDs often below the observed ones
- the most frequent number of families created in individual zones is shown in Figure 5 (we always choose only catastrophic disruptions with LBP < 0.3 and PB larger than 100 km)
- the Boulder collisional code operates with a random seed - for more reliable results we thus run 100 simulations

3. Results of 4 Gyr of collisional evolution (no LHB case)
- the most frequent number of families created in individual zones is shown in Figure 5 (we always choose only catastrophic disruptions with LBP < 0.3 and PB larger than 100 km)
- we obtain the number of families in the whole main belt = 10 times larger

4. Results including cometary Late Heavy Bombardment and dynamical decay
- a typical dynamical evolution of a cometary disk: data from Vokrouhlický et al. (2008), see Figure 6
- a dynamical decay of the main-belt population according to Minton & Malhotra (2010)
- we obtain the number of families in the whole main belt = 10 times larger
- the number of families in the pristine zone is calculated as the ratio of the total number of bodies > 100 km to the number in the corresponding zone (Figure 7)
- the angular momentum of the families is calculated as the ratio of the total number of bodies > 100 km to the number in the corresponding zone (Figure 7)

5. Important role of the cometary-disruption law!
- a simple criterion for physical disruptions of comets: perihelion distance q and probability p that the disruption occurs in one timestep (q = 500 yr and p = 0.999)
- results: the numbers of families in the whole MB (Figure 12) may significantly decrease (down to non-LHB case) for various q, fixed p = 1.5 AU
- various p, fixed q = 3.8 AU

6. The "pristine zone" in the (e, sin J) plane
- up to 17 families were recognised (Figure 6), but most of them are either small or scattered events
- families confirmed by Sloan DSS colour indices (Parker et al. 2008) and WISE albedos (Masiero et al. 2011)

7. Itha family: a dynamical model
- initial conditions: isotropic velocity field with size-dependent v = 10 v, = 90 m/s for D < 5 km
- random spin axes orientations
- 4-body simulation: SMVTP by Levison & Duncan (1994), with Vokrouhlický/YORP effect included
- hemispherical parameters: bulk density ρ = 2.5 g/cm³, surface density = 1.5 g/cm², conductivity K = 0.001 W/Km, C = 4000 K, Bond albedo A = 0.1, emissivity ε = 0.9
- spin evolution: YORP moments by Čapek & Vokrouhlický (2004), collisional reorientations
- synthetic family: initially extends beyond 5:2 and 7:3 resonances (Figure 9)
- moreover, there is a weak 12.5 MN/M (Figure 9) which is populated by families members sufficiently
- results: the number of families created is shown in Figure 10
- results: the number of families created is shown in Figure 10
- a preliminary estimate of the lower limit for the age is 4 Gyr (to dispense family members sufficiently)

8. Itha family: collisional evolution (without the LHB)
- parent body size: the method of Durda et al. (2007) based on a set of SPH simulations and fitting of D = 10 km part of the SFD (which is not evolved significantly); the best fits were from D = 70 to 130 km simulations with the Boulder code (with a similar setup as above)
- results: we can fit the observed SFD with a relatively small PB (D = 70 km), with a lower limit for the age 2 Gyr, but a larger PB (D = 100 km) is equally possible, with the age approaching 4 Gyr (Figure 10)

9. Itha family: a model including the Late Heavy Bombardment
- a single family created at the beginning of the LHB
- no physical disruptions of comets in this simulation
- the method of Durda et al. (2007) cannot be used in this case
- a sufficiently large synthetic family (D > 200 km) can 'survive' the whole LHB and resemble the observed SFD
- however, dynamical perturbations induced by planetary migration may destroy the compact family in the proper element space (Brož et al. 2012)

Conclusions
- using a combination of dynamical/collisional model we confirm that the Itha family may be > 3.8 Gyr old and may have experienced the Late Heavy Bombardment
- future work: test if a single scaling law can be used for the whole MB or not studies of dynamical/collisional evolution of other families in the pristine zone
- independent models for physical disruptions of comets would be extremely useful to constrain collisional models

References
- Durda et al. (2007), Icarus, 186, 498
- Brož et al. (2012), Icarus, 221, 121
- Hahn & Malhotra (2005), Icarus, 179, 51
- Wong & Malhotra (2005), Icarus, 179, 97
- Morbidelli et al. (2009), Icarus, 202, 310
- Vokrouhlický et al. (2008), AJ, 136, 1463
- Durda et al. (2007), Icarus, 186, 498
- Kobayashi et al. (2004), Icarus, 161, 121
- Vokrouhlický et al. (2008), AJ, 136, 1463

Figure 1: Six parts of the main belt in the proper semimajor axis vs inclination plane.

Figure 2: The observed SFDs of the six parts of the main belt.

Figure 3: The nominal scaling law used in our simulations.

Figure 4: The final SFDs of individual parts of the main belt after 4 Gyr of collisional evolution. We show the currently observed SFD (black line) and the initial SFD (gray line) for comparison. A conservative completeness limit is D = 10 km.

Figure 5: The histograms of number of families in individual zones. The currently observed number of families is displayed by points. Graph is zoomed to better view the most frequent number of families in the Cybele zone is 0.

Figure 6: The temporal evolution of the intrinsic collisional probability (bottom) and mean collisional velocity (top) computed for collisions between cometary-disk bodies and the main-belt asteroids.

Figure 7: The histograms of number of families for the simulation which include the cometary LHB and the dynamical decay of the MB population. Majority of the D > 100 km families were 'erased' by secondary collisions.

Figure 8: Proper eccentricity vs inclination for bodies in the pristine zone. Sizes of symbols correspond to actual diameters.

Figure 9: Proper semimajor axis vs eccentricity for the synthetic family (black) and observed members (red). The initial conditions as well as the situation at 1 and 4 Gyr are shown. Note that the number of synthetic bodies was selected 10 times larger.

Figure 10: The final SFDs of the synthetic family (and the MB) for three different initial SFDs. Note that for the largest PB of D = 130 km we cannot fit the observed SFD within 4 Gyr (nevertheless, see below).

Figure 11: The final synthetic SFDs for the simulation including the LHB 'tail'.